SMART MATERIAL POWERED ELECTROHYDROSTATIC ACTUATORS

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SUMMARY #1 -- PROGRAM OBJECTIVE AND SCOPE

AIM: **Develop a power-by-wire actuator small enough for unmanned aircraft**

SMART MATERIAL ENABLER: **Replacement of the rotary piston pump in a developmental Electro-Hydrostatic Actuator (EHA) with a high frequency magnetostrictive solid state pump**

Phase-1 Scope:

- **Demonstrate a brassboard high power density smart-material pump connected to an electro-hydrostatic actuator**
  - **1-in stroke @ 1000 lb load (3.5 ins/sec)**
  - **15-Hz bandwidth**

Phase-II Scope:

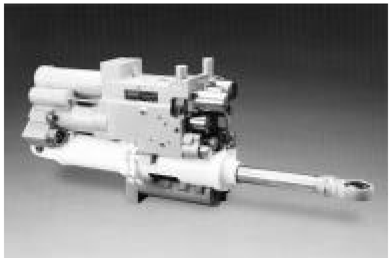
- **Fully integrate Smart Material pump with EHA to meet the requirements of the X-36 unmanned aircraft (-65°F to 275°F)**

SUMMARY #2 -- PROGRAM MILESTONES & STATUS

Program has not started

Task Name / Deliverable	Program Year1				Program Year2				Program Year3			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
PHASE I: Brassboard Demos												
Develop smart material pump												
Develop power conditioning												
Demonstrate actuation by pump												
PHASE II: Actuator Demo												
Modify pump/electronics for integration												
Modify EHA configuration for integration												
Integrate pump and actuator												
Compact actuator performance tests												

smart material pump externally connected to EHA to replace rotary pump



Integrated smart material powered EHA

Evaluated against X-36 system requirements

SUMMARY #3 -- ROLES AND RESPONSIBILITIES

System Element	Tasks (Organization)	Team Member
Smart Material Pump	**Design and fab. piston driver**	***Active Signal***
	Design & fab. smart material check valve	
	• Model dynamics of driver and valve • Select design and fab valve	***Active Signal***
	• Model fluid flow through valve • Optimize phase relation with piston	***Moog***

System Element	Tasks (Organization)	Team Member
Power Electronics	**Design & fab power electronics**	
	• Model V,i requirements of driver • Select design and fab/buy electronics	***Active Signal***
	• Model characteristics of candidate designs	***Virginia Power Technologies:***

System Element	Tasks (Organization)	Team Member
System Integration	**Design / fab hydraulics & actuator**	***Moog***
	• Model fluid flow/loss in hydraulics • Design hydraulic controls / safety / redundancy • Assemble & test brassboard actuator	

SUMMARY #4 -- MAJOR ACCOMPLISHMENTS OF PAST YEAR

Model contract has been received from the Air Force and reviewed

We plan to have a working testbed demonstrating smart material pumping by the next TIM

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SUMMARY #5 -- LESSONS LEARNED / TRANSITIONS

Major transition is to distributed flight controls

- **Fly by wire / power by wire**
- **Unmanned aircraft such as the X-36**
- **Moog is a world leader in aircraft actuators**
- **New procurements such as JSF and next generation Airbus may specify all-electric actuation**

Secondary transition to underwater craft and weapons flow controls

- **Large stroke/high force up to 1 kHz for rapid maneuvering**
- **More stable temperature environment allows PMN to be used to increase power density**

TECHNICAL OVERVIEW

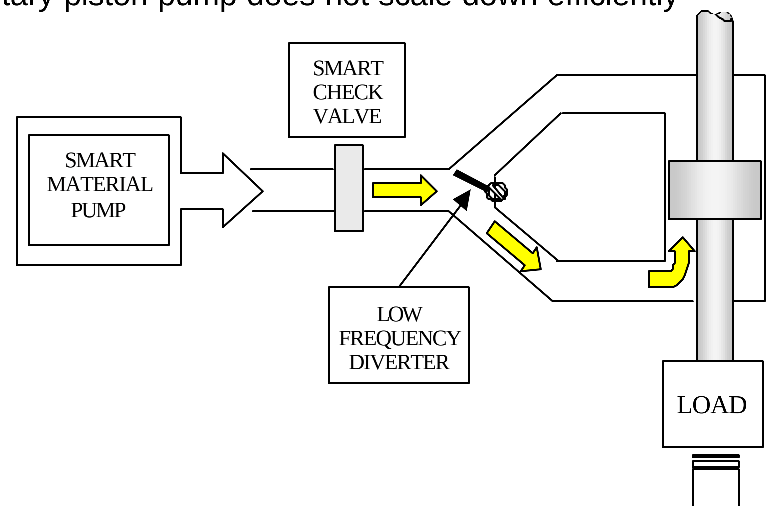
Existing Electrohydrostatic Actuators (EHA's) provide mature experimental platform for delivering *power-by-wire*

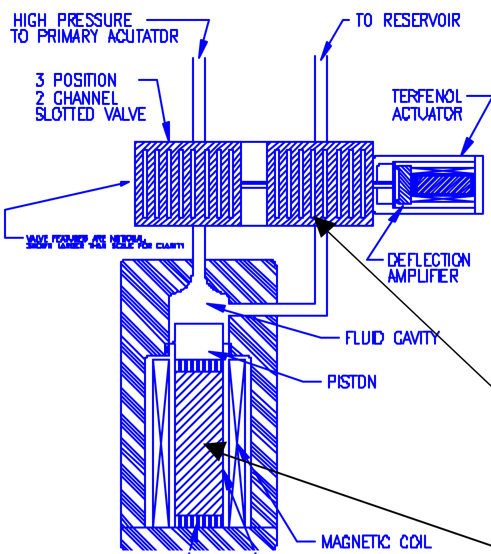
Smart material pump enables the EHA to be scaled to compact size and high power density

MOOG slave hydraulic actuator

Conventional Hydraulics provide large stroke and force but employ complex fluid pressurization and delivery systems

Electrohydrostatic Actuators generate pressure locally thereby eliminating the "hydraulic infrastructure" but rotary piston pump does not scale down efficiently





Lightweight, stiff check valve

Smart material driver

Smart Material pump concept

Solid State Pump delivers **scaleable** high power densities up to ~10 kW/kg at high frequencies. Smart check valve converts this to low frequency, high stroke

SMART MATERIAL SELECTION -- THERMAL LIMITATIONS

Piezoelectric losses (tanδ) increase with temperature

- **heating limits drive at high power / high duty cycle to solid lines below**

PMN has losses (tanδ) that decrease with increasing temperature -- self limiting

Terfenol performance much less temperature dependent than PZT or PMN

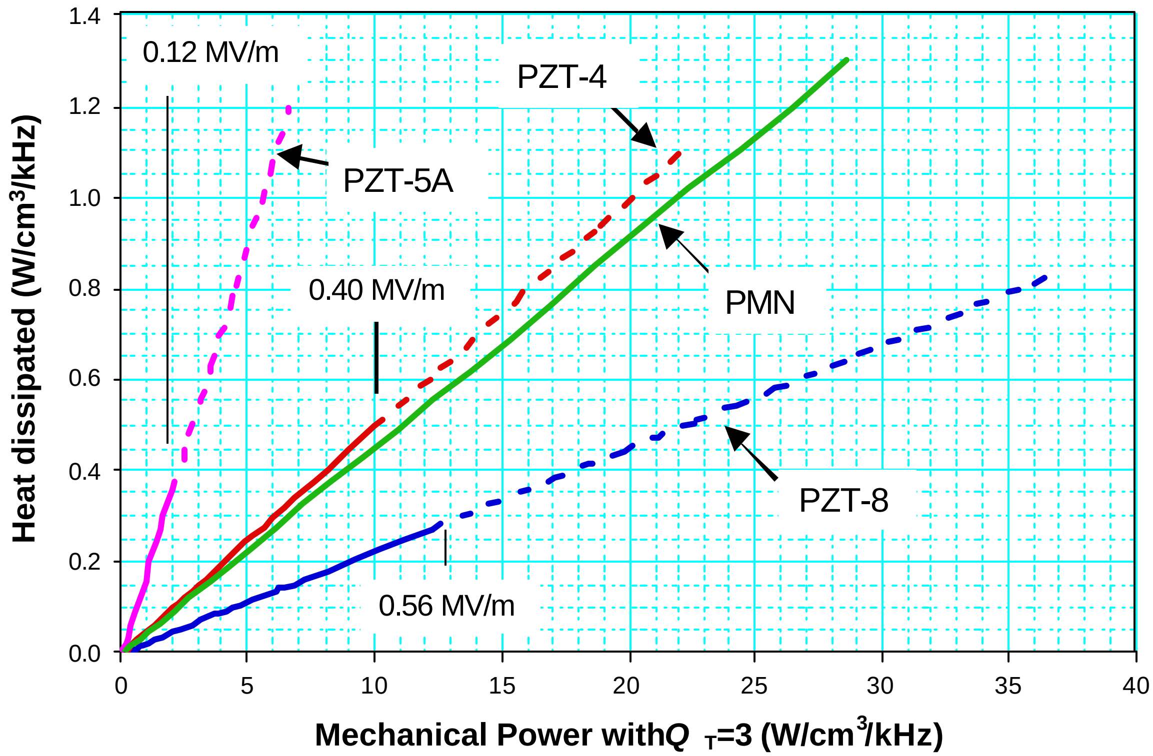
Intrinsic mechanical power, P_M

$$P_M = \frac{1}{2}\omega k_{33}^2 E_{rms}^2 \kappa_{33}^T \varepsilon_0 Q_T$$

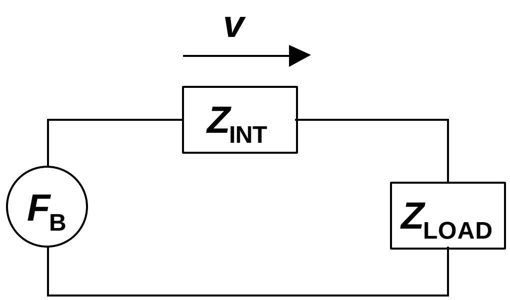
Heat dissipated, $P_{DE} + P_{DM}$

$$P_{DE} = \frac{1}{2}\omega E_{rms}^2 \kappa_{33}^T \varepsilon_0 \tan\delta$$

$$P_{DM} = \frac{1}{2}\omega E_{rms}^2 k_{33}^2 \kappa_{33}^T \varepsilon_0 \frac{Q_T^2}{Q_M}$$



SMART MATERIAL PUMP DRIVER -- INTRINSIC POWER DENSITY



Assume max power transfer for $Z_{INT} = Z_{LOAD}$

For stiffness, k, controlled impedance $Z = k/w$

Effective power density, $P = \frac{1}{2} F_B v$

Rearranging ➔ $$P = \frac{1}{4} Y S^2 w$$

		POWER DENSITY (W/kg)				
	Materials:	**PZT-8**	**PZT-4**	**PZT-5**	**PMN**	**Terfenol-D**
	Modulus (Gpa):	74.1	64.5	47.9	70.0	30
	Max rms drive field (MV/m):	0.56	0.4	0.12	0.4	-
	Max rms strain (-):	0.0134%	0.0128%	0.0066%	0.0320%	0.0318%
	Density (kg/m^3):	7800	7800	7800	7900	7800
100		27	21	4	143	61
200		54	43	8	285	122
500		135	106	21	713	306
1000	**Frequency (Hz)**	269	213	42	1,425	612
2000		539	426	84	2,850	1,223
5000		1,347	1,064	210	7,126	3,059
10000		2,695	2,129	420	14,252	6,117

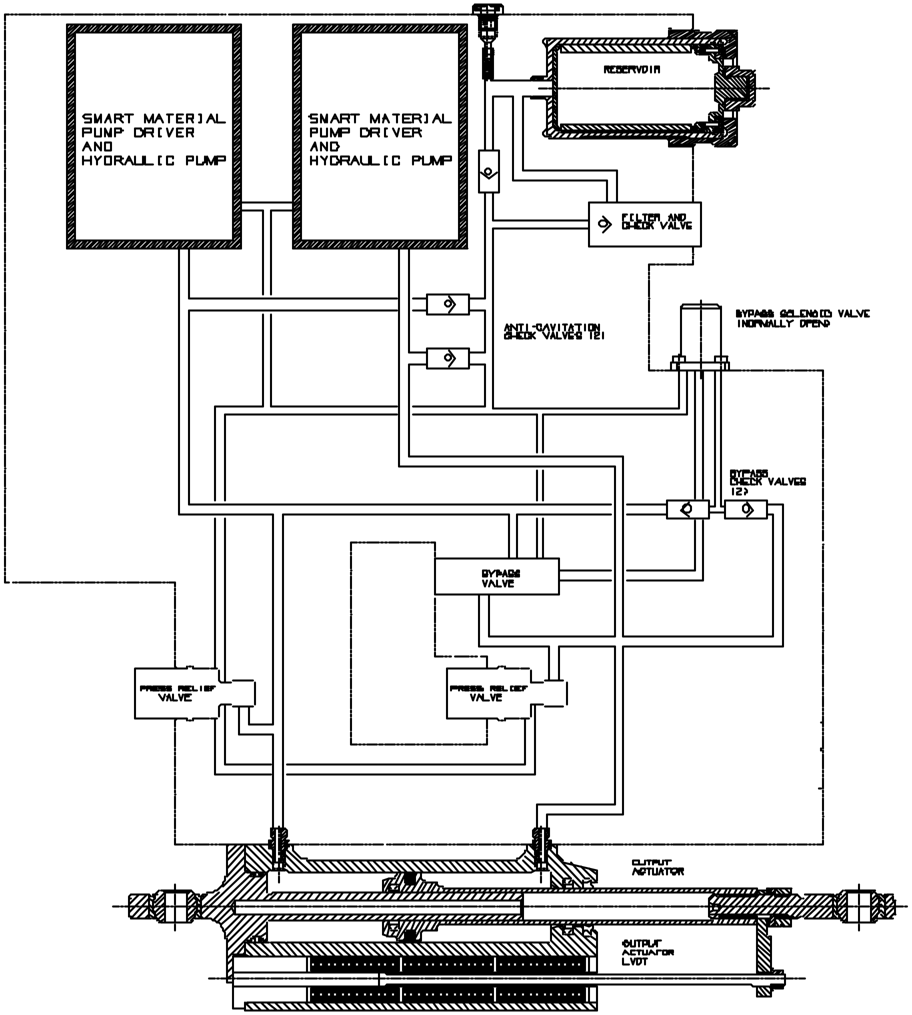
"LOCAL" HYDRAULIC DESIGN

Hydraulic design incorporates:

- **distributed lumped parameter model of closed system**
- **redundancy / overpressure releases / cavitation**

Design concepts based on:

- **CAD/CAE designs**
- **EHA prototypes**
- **MATLAB models of response times, flow, pressure drops, leakage**
- **empirical data on damping characteristics of the system**



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CONCLUSIONS

- **A smart material pump potentially enables self-contained EHA within the tight packaging requirements of unmanned aircraft**

- **By incorporating the smart material pump into an existing, tested EHA prototype, the development effort is focused entirely on the smart material driver and corresponding smart check valve**

- **Very high frequency piston operation results in high power density, and fluid pumping is enabled at these frequencies by an active check valve**